Pros, Cons, and Alternatives to Weight Based Cost Estimating

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Many cost estimating tools use weight as a major parameter in projecting the cost. This is often combined with modifying factors such as complexity, technical maturity of design, environment of operation, etc. to increase the fidelity of the estimate. For a set of conceptual designs, all meeting the same requirements, increased weight can be a major driver in increased cost. However, once a design is fixed, increased weight generally decreases cost, while decreased weight generally increases cost – and the relationship is not linear.

Alternative approaches to estimating cost without using weight (except perhaps for materials costs) have been attempted to try to produce a tool usable throughout the design process – from concept studies through development.

This paper will address the pros and cons of using weight based models for cost estimating, using liquid rocket engines as the example. It will then examine approaches that minimize the impact of weight based cost estimating. The Rocket Engine Cost Model (RECM) is an attribute based model developed internally by Pratt & Whitney Rocketdyne for NASA. RECM will be presented primarily to show a successful method to use design and programmatic parameters instead of weight to estimate both design and development costs and production costs. An operations model developed by KSC, the Launch and Landing Effects Ground Operations model (LLEGO), will also be discussed.

Nomenclature

AFPL	= Air Force Propulsion Laboratory
ASE	= Advanced Space Engine
CER	= Cost Estimating Relationship
ELV	= Expendable Launch Vehicle
FY	= Fiscal Year
G&A	= General & Administrative
GG	= Gas Generator
KSC	= Kennedy Space Center
LH_2	= Liquid Hydrogen

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LLEGO	= *Launch & Landing Effects Ground Operations (model)*
LOX	= Liquid Oxygen
MSFC	= Marshall Space Flight Center
NAFCOM	= NASA Air Force Cost Model
NASA	= National Aeronautics and Space Administration
PWR	= Pratt & Whitney Rocketdyne
RECM	= Rocket Engine Cost Model
SSME	= Space Shuttle Main Engine
STME	= Space Transportation Main Engine
TAAF	= Test, analyze, and fix
TFU	= Theoretical First Unit
TQM	= Total Quality Management
UCR	= Unsatisfactory Condition Report
US	= United States
USAF	= United States Air Force
WBS	= Work Breakdown Structure

Introduction

MANY cost estimating tools use weight as a major parameter in projecting the cost. This is often combined with modifying factors such as complexity, technical maturity of design, environment of operation, etc. to increase the fidelity of the estimate. For a set of conceptual designs, all meeting the same requirements, increased weight can be a major driver in increased cost. However, once a design is fixed, increased weight generally decreases cost, while decreased weight generally increases cost – and the relationship is not linear.

Alternative approaches to estimating cost without using weight (except perhaps for materials costs) have been attempted to try to produce a tool flexible enough to be employed throughout the design process – from concept studies through full scale development.

This paper will address the pros and cons of using weight based models for cost estimating, using liquid rocket engines as the example. It will then examine approaches that minimize the impact of weight based cost estimating. The Rocket Engine Cost Model (RECM) is an attribute based model developed internally by Pratt & Whitney Rocketdyne for NASA. RECM will be presented primarily to show a successful method to use design and programmatic parameters instead of weight to estimate both design and development costs and production costs. An operations model developed by KSC, the Launch and Landing Effects Ground Operations model (LLEGO), will also be discussed.

Cost Model Needs

During the conceptual design of rocket engines, and during the parametric survey of engines for architecture studies, only limited design information is available. The information available is really the parameters being examined, e.g., thrust, engine power cycle, choice of propellants, chamber pressure. Nonetheless, the cost of the options is generally wanted to help make choices among the options. Further, questions about how to change the cost for various options will also be asked, e.g., the impact of how the engines are produced, of the rate of production, of the degree of government oversight, of the quantity and duration of testing, including a quantification of the certification approach, etc.

The costs generated need to be accurate both in absolute value and relative to the options considered or else the trades will be decided incorrectly.

What type of cost model can be used at this level of design and give the quantitative and qualitative answers needed? Ideally the cost model will use as inputs the parameters that drive the design and identifies the elements in the design with the most significant impact on cost or the investment.

Types of Cost Models and Their Pros and Cons

A cost analyst tasked with providing a cost estimate for a new program faces numerous dilemmas. Very early in the process, there is not much information about the planned program, yet there is a desire to determine the costs and the costs of various trades. As a program goes forward, space systems tend to

mature information about product performance well ahead of information useful to cost analysts. The program tends to start settling parameters such as orbits and power levels well before deciding on specific technologies, which the costs analyst needs to really understand costs. As information useful to a cost analyst does mature and settle into a set of compatible pieces of information, this tends to be because decisions have already been finalized, making the cost estimate a formality in the process, not a part of the design. Cost (and the infamous cost over-run) becomes an output of the process rather than an input into the program's design and development.

One idea that has been used to address the cost analyst's dilemma is weight based cost estimating. Under the proper circumstances, weight based cost estimating can be quite accurate. Assume that a program wants to build something similar to something that has previously been built, and further assume there is excellent cost data for that item in a well maintained database. A cost analyst could then use the planned weight of the newly planned items to locate the past item's cost data in that database. With adjustments for weight and inflation, the cost for doing the same thing again could be very close to the cost the last time it was built. The challenge begins when modifying the new item in relation to the one in the database. As modifications are made to the new item's details, its technology, its production or operations processes, the experience of the specific organization making the item this time (not the organization who did it last time), its scale, its testing plan for reliability, and so on, the database becomes less applicable and the cost estimate loses accuracy. Lack of properly adjusting for these factors, leaving weight as the principal driver, produces the primary limitations of weight based cost estimating.

The accuracy of weight based cost estimating can be improved by adding many more, and much more varied, items to the database, along with determining various "complexity" factor to account for differences between the items in the database and the new item. Thus, traditionally, cost models are based on two key parameters: weight as a general indicator of size, and some complexity parameter, or parameters, to distinguish between the costs of items with the same weight.[1] However, there are other approaches: process based[2], feature based[3], and part counts[4] have all been proposed. Combinations of these approaches can also be used[5]. Another approach is to develop cost models based on the functional parameters that actually produce the differences in the resulting costs. These are functional parameter based cost models.

Many of these models rely on regression analysis of a database. Depending on what parameters are used for the analysis, the resulting model may not yield much engineering understanding of why the results are changing in a particular way. Weight is often used as a parameter with the cost commonly increasing when the weight increases. However, in rocket engine design higher weight is often related to decreased cost. Indeed it is often the means used to reduce cost by relaxing various requirements or by using materials that are less costly in manufacturing processing but lower in strength, thus increasing weight.

Models that rely on being feature or process based are really models for fairly well developed designs, and the detail needed to use them is not available at the conceptual design level. The same is true of models based on part counts.

WBS based models require significant effort to develop the detailed WBS needed for accurate costs. The effort is beyond what is reasonable at this design level. Also, very detailed WBSs would be required to trade such options as chamber pressure or propellant type to show a differentiation.

PRICE H, SEER-H, TRANSCOST, and NAFCOM are models commonly used for space launch or spacecraft cost modeling. Within those models are sub-models that either can be used for rocket engine cost modeling via correlation of parametric functions, or the sub-models can use regressed data to create surrogate rocket engine cost models.

PRICE H is part of a modeling solution set that is provided by Price System Solutions LLC[6]. PRICE H is a desktop software package that applies parametric modeling techniques to provide estimated cost of components or systems. PRICE was originally developed under RCA and later Lockheed Martin. PRICE TruePlanning© is the latest in the cost and economics analysis software sets offered by PRICE. PRICE H provides hardware development and acquisition cost based on a composite of sub-programs that have their predictions based on what PRICE refers to as "industry-specific" parametric cost models that are benchmarked with "factual" data. Correlation of the models is obtained by alignment of weights and sub-element dependency to capture parametric interactions. The inter-element alignment is based on what the user provides during the model "build" state via the general inputs to the model. PRICE H is dependent on the system weight and the capability of the user to provide accurate (valid) values that define the additional correlations that creates the cost estimating relations or parametric functional cost estimations.

The TruePlanner software enhances PRICE H by applying the FRISK/Method of Moments methodology that is based on applying triangular distributions within a probabilistic approach against the

weight-based core algorithms. Again the inter-elements alignment is based on user defined correlations. Figure 1 shows a screen shot of a PRICE run.
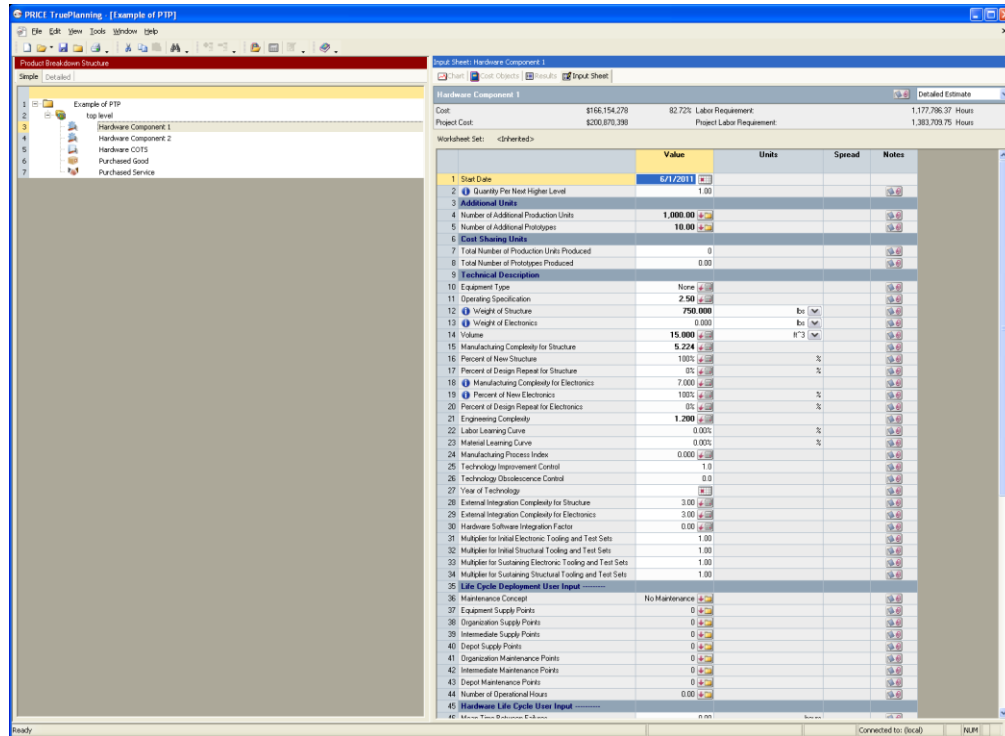

Figure 1. PRICE H screen shot.

SEER is a software tool created and marketed by Galorath Incorporated and the SEER-H model element is used to represent hardware, electronics, and systems development and acquisition costs. The SEER-H website refers to SEER-H as providing "total cost of ownership for new product development…". The SEER-H cost estimating functions are taken from a database that is tied to historical projects, behavioral models, and other internal metrics. Additionally, SEER-H applies expert "knowledge bases" and statistical capabilities to the cost estimation. SEER-H also includes methods of risk assessment for the defined project. The primary parameters used to define the system element for parametric system cost estimating are the weight, the volume, and the assignment of the elements to the SEER database[7,8].

TRANSCOST was developed by D. H. Koelle initially while at Messerchmitt-Bolkow-Blohm (MBB) in 1988. Since then more data has been added to further anchor the relationships. TRANSCOST is based on regressed data from historical program system elements that are used to create mono and bivariate cost estimating relationships. These relationships are combined in the TRANSCOST model to describe the unit, production, development, and operational (per launch) costs. The model is specific to expendable and reusable launch systems. It provides terms to adjust the relationships for variations in production rate, testing, flight rate, propellant types, and rocket engine types. The predominate correlation of the data is based on historical United States rocket engines and launch systems with some non-US systems and undeveloped concepts also used in creating the cost estimating functions. TRANSCOST can be referred to as a "Statistical-Analytical" weight-driven cost model with complexity factors in the relationships to permit anchoring and tailoring to match an expected total cost of the system. The TRANSCOST model presents itself as best for providing trends for variations in a "defined" aerospace system more so than predicting the "absolute" cost for the concept, since most of the relationships are based on programs that were driven by government oversight and procurement practices. TRANSCOST is unique in that is presents the cost in terms of manyears which can be converted to the "then-year" labor rates in any industrialized country. The rocket engine cost model in TRANSCOST is driven predominately by the weight or mass of the engine systems and the type[8,9]. Figure 2 shows some of the data used in developing TRANSCOST.
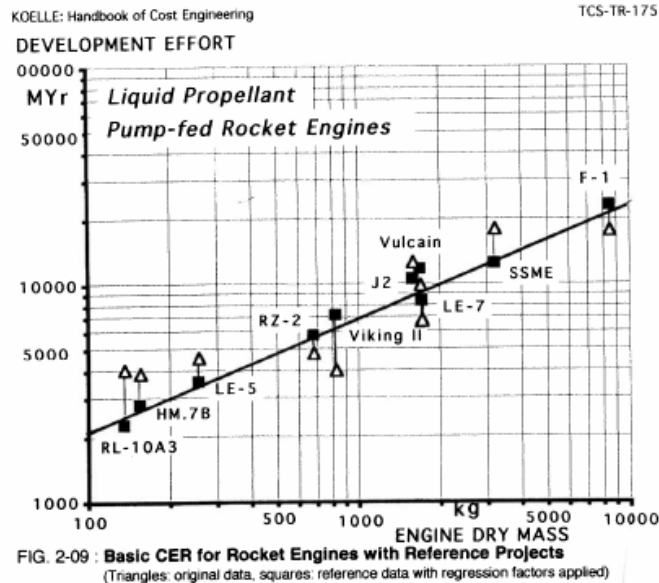
Figure 2. TRANSCOST liquid rocket cost data used to create rocket CER.

None of these models are explicitly based on the functional parameters and program choices being examined during rocket engine conceptual design.

NAFCOM is a cost model that does address, in the liquid rocket engine part, these concerns. NAFCOM is a similarly database correlated program of cost estimating functions developed collaboratively by NASA and the USAF using proprietary program cost data from many American aerospace programs[10]. NAFCOM is dependent on the weight of the system or subsystem elements to describe the cost for parametric evaluation. Additionally, complexity terms, production rate, the application (in terms of environment - manned or unmanned, expendable or reusable, etc.), and other clarification coefficients can be determined from the user's input to describe the system or system elements. NAFCOM has an extensive aerospace system database that is used to create the subsystem unit, development, and post-development costs. The database is not available for review or refinement of the data regression that produced the CERs since it is created from various aerospace companies' proprietary program cost data. The rocket engine cost model in NAFCOM is derived from the Rocket Engine Cost Model described later in this paper and does address functional parameters and program choices. This model was created with the intent that the user needed more accuracy and insight into the algorithms. Figures 3 and 4 show examples of the system and the engine model input screens.
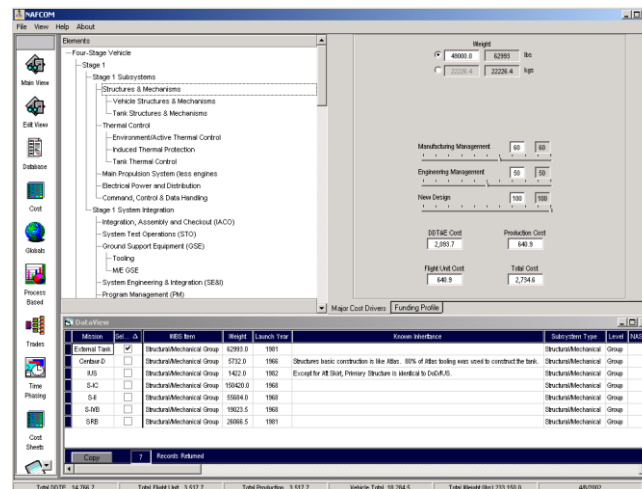

Figure 3. NAFCOM example of the user interface to create a system cost model.

Figure 4. NAFCOM example of the user interface for using the liquid rocket engine component.

Recent enhancements to NAFCOM's probabilistic tool makes it more capable of representing new start or commercial aerospace programs when the correct economic and investment assumptions are included. But it typically can take several iterations with component and system design experts to adjust the foundational model so that can it be used to address the "should cost" development and unit cost of conceptual aerospace systems.

The primary issues with all the above cost modeling capabilities relative to liquid rocket engine conceptual cost prediction are that the correlations are performed with very specific program data that may or may not be relevant to the concept; that several complexity terms must be adjusted, aligned, and anchored to create an association to the system or subsystem concept and this can introduce significant prediction errors; and that the process of calibration of the complexity factors is user or peer group knowledge biased which can introduce more variability into the statistical errors that already exist.

Moreover, using historical program costs directly to predict the cost of future technology or new start aerospace concepts requires more detail in the design than is available at the conceptual design level to reduce the variability.

Consequently, the current weight based models do not provide adequate simulation of conceptual system development cost without extensive qualification of the details of the conceptual design to produce accurate analogs.

An alternate approach is to directly address the functional parameters and program choices being considered and produce a cost model based on them. Such an approach uses what is actually available in conceptual design and, more importantly, permits engineering and programmatic insight into what is driving the results. As reference 1 concluded, during the conceptual design phase, functional parameter based cost models would appear more logical for production and development cost estimates, since they are based on the design parameters that directly drive the costs.

Non-Weight Based, Non-Regression Based, Functional Parametric Cost Models

Two models will be discussed, the Rocket Engine Cost Model and the Launch and Landing Effects Ground Operations model.

The Rocket Engine Cost Model (RECM) is an example of a non-weight based, non-regression based, functional parametric based cost model. It was prepared by Pratt & Whitney Rocketdyne (PWR) for NASA in 1993[11] and updated in 2000[12]. It is incorporated, with NASA modifications, in the liquid rocket engine part of the NASA NAFCOM cost model.

RECM was specifically designed as an alternative to weight based cost estimating tools. It was developed to be able to estimate costs, both development and production, for liquid rocket engines at the architecture, conceptual, and early design stages of definition. During those stages, weight information is difficult to generate and is suspect. The information that is available is really design choice information – thrust, chamber pressure, engine power cycle, etc. It was desired to be able to assess the cost impact of these types of choices, and of production and management approaches, in order to help make decisions about what design choices to pursue for various different missions and requirement sets. Consequently, RECM is an example of how it would be desirable to construct a conceptual design stage functional parameter cost model.

The remainder of this paper will provide a brief overview of RECM and then describe what its inputs are and how they influence its results. The emphasis is on what the inputs are and how they allow conceptual level studies to be addressed using the parameters and choices available at the conceptual design point in the design cycle.

The objective of RECM was to use historically-based, parametric cost estimating relationships (CERs) at the engine level for estimating development and production costs of chemical propulsion, liquid propellant rocket engines in the 20 Klbs to 2,000 Klbs vacuum thrust range.

The need for this objective was the lack of engineering and programmatic parameter cost models for rocket engines. Several parametric production cost models for rocket engines have been developed in the past, but these models are based on regression analysis and do not always have the right independent parameters. They also lack prediction of engine costs for other than performance optimized engines.

The purpose is to enable parametric estimation of new or restarted engine production costs, check the validity (sanity check) of rocket engine costs provided by others, and identify cost driving technical and programmatic parameters.

The cost modeling approach is divided into two parts: a production cost model and a development cost model. Both models contain parametric CERs which give cost as a function of size, complexity, and process attributes. Cost Breakdown Structures define the individual cost elements to which the CERs are applicable. The development component and production component both provide cost estimates based upon measures of thrust, complexity and various process attributes.

The cost models are to be understood as engineering models and are not based on regression analysis, since they are using only a few data points. The CERs are anchored (calibrated) with the technical and cost data of PWR's engines. Cost data were obtained from company records, not from government sources, for traceability and "purity" reasons.

Production rate and quantity effects were also obtained from PWR's historical database. The influences of these significant factors on hands-on labor, support labor, and material cost were combined using PWR's process-oriented production cost model.

The development cost model part of RECM uses "real world" cost drivers such as engine complexity, maturity, test frequency, process improvement factors, etc. Considerable insight into development cost driving parameters were obtained by analyzing in detail the available engine development program cost breakdowns.

The cost models are intentionally simple in order to be useful in the early program phases of future engines when few parameters are known[13]. Technical and programmatic descriptions of an engine are input into the cost model and are translated into cost parameters via CERs, judgmental factors, and engineering estimates. The cost models quantitatively characterize the engineering and manufacturing knowledge base.

Development cost data used is from the F-1, J-2, SSME, J-2S, RS-27, MA-5, MA-5A, X-33, and Fastrac programs.

Production cost data is from the F-1, J-2, J-2S, RS-27, MA-5, SSME, X-33, and Fastrac programs.

Program data and program cost analysis from STME, Peacekeeper Stage IV, Lance, ASE, and other PWR engine programs were also included in the development of parametric relationships and factors.

The basic ground rules and assumptions for the rocket engine cost estimation model are:
- Contractor recurring costs only
- Fiscal year 1992 constant dollars
- Include all costs through G&A expense
- Unit costs include:
  - Base fabrication
  - Manufacturing services
  - Recurring tooling and material

- o Inspection and quality engineering
- o Program management
- o Sustaining engineering
- o Purchased material, components and overheads
- o Acceptance labor
- o Contractor fee
- o Propellants
- Excluded cost elements:
  - o Nonrecurring tooling, ground support and special test equipment
  - o Facilities
  - o Government support.
  - o

The characteristics of the engines used as anchor points are shown in Figure 5.

	F-1	RS-27	MA-5 Booster	J-2	J-2S	SSME	ASE	X-33	Fastrac
Thrust (vac)	1748	237	463	230	265	470	20	206	60
Cycle	GG	GG	GG	GG	Tapoff	SC	SC	GG	GG
Propellants	LOX-RP-1	LOX-RP-1	LOX-RP-1	LOX/LH$_2$	LOX/LH$_2$	LOX/LH$_2$	LOX/LH$_2$	LOX/LH$_2$	LOX-RP-1
Chamber Pressure (psi)	982	700	639	736	1250	3300	2000	854	633

Figure 5. Engines used as anchor points in RECM.

Production Cost Model Description

The production cost model is a simple model as previously mentioned. Primary inputs are vacuum thrust, thermodynamic engine cycle and type of propellants. The production cost category includes all hands-on and support manufacturing labor, procured hardware from subcontractors and raw material, engineering support, production management and acceptance testing. The elements contain all engine contractor and component subcontractor cost items through general and administrative expenses (G&A), including all fees.

A basic CER was constructed, shown in Figure 6, that relates theoretical first unit (TFU) cost at 30 units per year (in 1992 $) to the three primary inputs. Adjustment factors were generated to modify this TFU cost for chamber pressure (Pc), reusability (REUSE), manufacturing improvement (IMP), production rate (RATE), production quantity (Q), automation effect (CIM), dollar escalation factor (ESC) and contractor fee (FEE). All adjustment factors are multiplied with each other and with the TFU cost from the CER to yield the unit production cost under the input conditions. The escalation factor (ESC), considers inflation and adjusts the CER to any desired constant fiscal year dollar level. The fee factor (FEE) can be input as either one, yielding cost, or greater than one, yielding price. All factors are independent of each other.
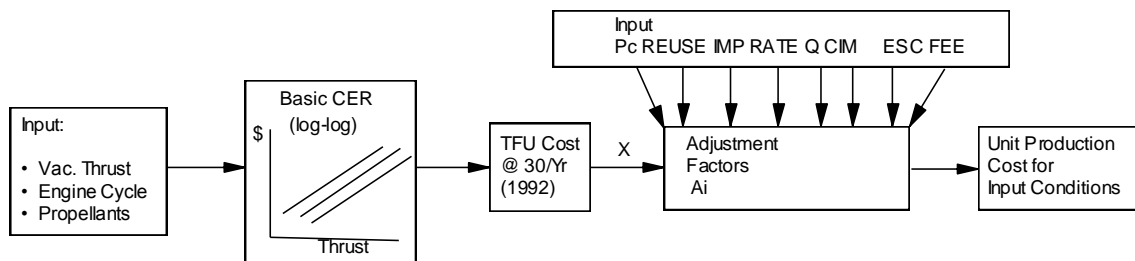
Figure 6. Production cost model.

Figure 7 shows the cost normalization process. It uses PWR's Process Oriented Production Cost Model, originally developed under a NASA MSFC contract as an STME turbomachinery cost model, and, separately with AFPL funding, as an STME combustion devices cost model[14]. It was further enhanced as an engine production cost model using company funding.
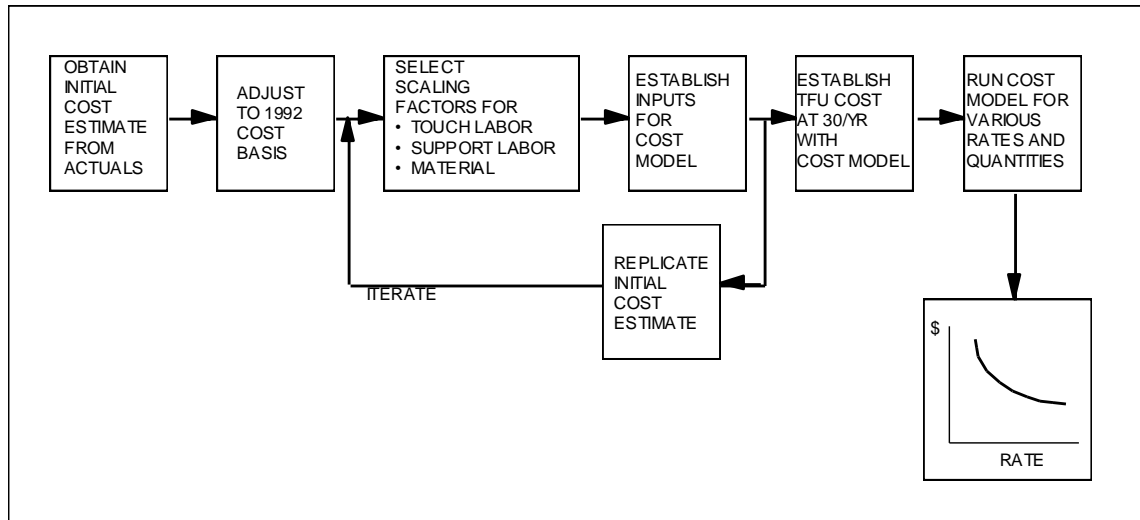
Figure 7. Cost Normalization process.

An initial single cost data point from actual production records is obtained for each engine, broken down into touch labor, support labor, and material. The cost basis is normalized to FY1992 dollars using the above-mentioned NASA escalation factors. Since the cost normalization is with respect to quantity (quantity of one for theoretical first unit, TFU) and rate (thirty per year), individual scaling factors are selected for touch labor, support labor and material costs. These, and other parameters, are input into the process-oriented cost model and iterated until the initial cost estimate is replicated. This way, the TFU cost at thirty units per year is established. The model can now be exercised for different combinations of production rates and quantities. The process-oriented cost model was originally defined and calibrated with detailed RS-27 cost breakdowns.

The major inputs are discussed below and a list of the production cost input parameters, by type, are:

Size:	Thrust
Complexity:	Thermodynamic Cycle
	Propellant Type
	Chamber Pressure
	New Technology
Process Attributes:	Design Maturity
	Design Process Maturity
	Production Rate
	Production Quantity
	Improvement Curve Type
	Improvement Curve Rate
	Producibility Improvement Factor
	Manufacturing Process Maturity
	Manufacturing Automation Level
	Reusability
	Year Dollars
	Escalation Factor
	Fee

The chamber pressure adjustment factor is of parabolic nature and adjusts the TFU cost between pressures of 500 and 3,000 psi (1,000 psi for GG, 3,000 psi for staged combustion). It is a second order magnitude effect on cost.

The relative first unit cost factor for chamber pressure adjustment is a function of chamber pressure. The curves were developed parametrically for open and topping cycle engines. The smooth curves are approximations for curves with step functions due to the addition or deletion of turbopump stages. The shape of the curves was developed from weight and cost considerations. As chamber pressure increases, the main combustion chamber size and weight decrease, but the turbomachinery weight and complexity (i.e., number of stages) increases. The two effects are of approximately equal cost magnitude and "fight" each other. The result is a parabolic shape for the curves. A gas generator engine with Pc=1,000 psia has about the same production cost as one with Pc=3,000 psi if all other parameters are held constant.

The reusability factor equals one for long life LOX/LH$_2$ staged combustion engines with SSME-similar life characteristics. It is less than one for expendable LOX/LH$_2$ staged combustion engines. This factor is greater than one for reusable GG engines, since the CER was based on expendable GGs. "Expendable" engines are those designed for less than twenty missions (i.e., it includes short-life reusability).

The three main areas of cost reduction due to differences between long life reusable and expendable engines are: component deletion, manufacturing process simplifications, and support labor decreases.

Reusable engines require a complex controller/computer with Health-Monitoring System function and the associated instrumentation, similar to aircraft engines. Besides manrating, this is required to ensure the return of high value assets, i.e., engines and vehicle. Redundancy is required (for example, in the control system) for the same reason. Flow shields are required for protecting the engines from the reentry environment. All these components can be deleted or greatly simplified for expendable engines.

Expendable LOX/LH$_2$ staged combustion engines do not need plated components, weld overlays (against hydrogen embrittlement) and wear coatings. In some areas, quality standards can be relaxed due to shorter life requirements. This affects the number and quality of fasteners and tolerance/defect/mismatch requirements for welds, materials, etc.

Expendable engines also require less support labor hours than reusable engines in the areas of quality control end sustaining engineering. In addition, the manufacturing wrap rates (due to support labor) will decrease since more expendable engines will be produced as compared to the number of reusable engines. This spreads support labor over more units and decreases the cost per unit.

The producibility improvement factor is one for all historical engines; it is less than one for the upcoming new approaches to "low cost" engines. This factor includes design simplifications and manufacturing improvements. Some concrete examples are: advanced fabrication methods, such as castings for hot gas manifolds and turbomachinery housings; some parts fabricated from sheet stock; inspection and cleaning redundancies and serialization requirements deleted or simplified; stringent constraints on weight growth relaxed, leading to the elimination of chemical/profile machining and material substitutions; and full implementation of Continuous Process Improvement, employee empowerment, Organizational Excellence, and Manufacturing Resource Planning to reduce the manufacturing support costs.

Even greater production cost decreases could be achieved for a truly expendable engine of new design with innovative low-cost design and manufacturing improvements. However, the performance of this engine would be lower than that of the historical engines.

The production rate factor equals one for thirty units per year; it is greater than one for lower rates. A cost improvement curve approach is used with rate substituting the normally used quantity.

The production quantity factor equals one for TFU cost, and is less than one for higher quantities. A normal cost improvement curve factor is used (also called "learning curve").

The automation effect considers Computer Integrated Manufacturing with a high degree of automation for production rates of 50 or more units per year.

The escalation factor is one for FY 1992 constant dollars. It is greater than one for previous year dollars and less than one for future year dollars.

The contractor fee factor converts engine unit cost (factor of one) to engine unit price (factor greater than one).

Development Cost Model Description

An analysis of the development program cost distribution of two engines (F-1 and J-2) has disclosed that the majority of the cost, more than 70%, is due to failure mode elimination as shown in Figure 8. The x-axis shows the percent of peak funding for each cost area. These charts account for the iterative test, analyze, and fix (TAAF) cycle of the component and engine development program. Only 2% was expended for the initial design effort, 15% for engineering design and analyses, mainly in the early part of the program, and 10% for qualification, reliability demonstration, and certification.
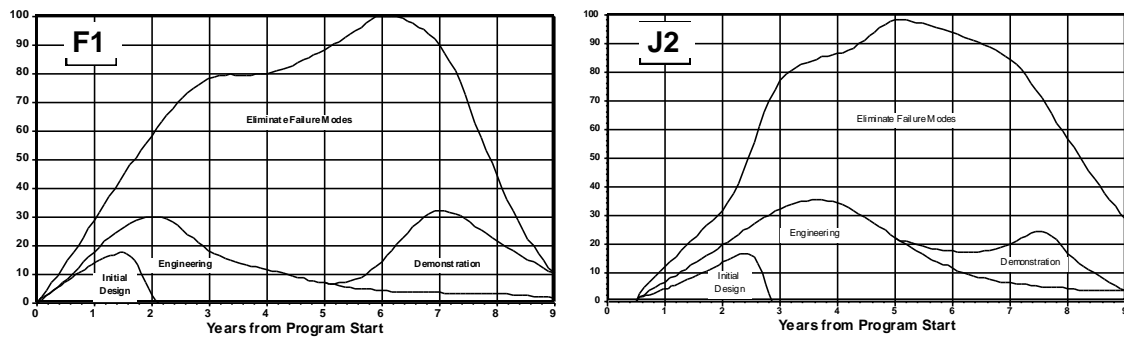
Figure 8. Historic rocket engine cost breakdown.

This indicates that a representative development cost model should address the number of tests required for the TAAF cycle as a key parameter. It also indicates that the number of tests is a cost driver which must be reduced to result in lower development costs. A development cost model that is keyed to engine size would not lead to appropriate CERs.

Thus, the core of the development cost model consists of the parameter "number of tests required." This parameter directly determines the test labor cost and the required quantity of development engines. Together with the engine unit cost obtained from the production cost model, the number of development engines defines the total development hardware cost. The cost of design engineering/analysis and of tooling, ground support equipment, and special test equipment needs to be added to hardware and test cost to sum up to the development cost. Program management cost and fee are usually estimated as a percentage of the development cost. The cost elements are aggregated to total development cost.

Figure 9 is an overview of all rocket engine development phases. The engine development cost model covers all phase C/D contractor efforts, from the end of phase B to the flight phase. Phase C/D starts with the fully defined requirements for the engine and ends with successful completion of the single engine certification program. After phase C/D the engine is certified for first flight.
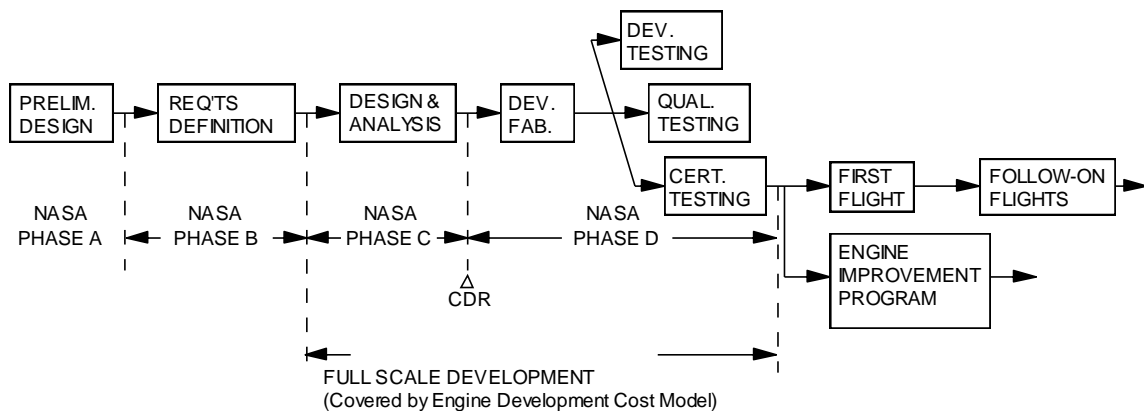

Figure 9. Overall program structure.

Figure 10 shows the structure of the development cost model. The model has eleven inputs. They consist of seven adjectively determined engine complexity and maturity indices and process improvement and tooling availability factors, and four objectively determined programmatic and unit cost inputs. The first group of seven adjective factors are judgmental in nature, but with a graduated scale given for metrification. The second group of four parameters are objective quantitative inputs. The inputs are:

Adjective Factors
- Engine Cycle/Internal Environment Complexity (CYPLX)
    - Measure of Cycle Complexity
- Engine Design/Manufacturing Maturity (ECMPLX)
    - Measure of Engine Maturity
    - Measure of Technology State-of-the-Art
- Tooling Availability Factor (TAVAIL)
    - Measure of Retooling Degree
- Test Quantity Process Improvement Factor (PIF1)
    - Expression of Testing Philosophy
    - Measure of Certification Approach
- Test Process Improvement Factor (PIF2)
    - Measure of Testing/Setup/Post Test Simplification
- Design Process Improvement Factor (PIF3)
    - Measure of Design Automation
    - Degree of Availability/Use of Advanced Design Technology
    - Degree of TQM Implementation
- Tooling Improvement Factor (TIF)
    - Measure of Tooling Modernization

Objective Factors
- Test Frequency in Tests/Month (TFRO)
- Development Engine Fabrication Time Span (DET)
- Theoretical First Production Unit Cost (TFU)
- Anticipated Engine Production Rate (R2)
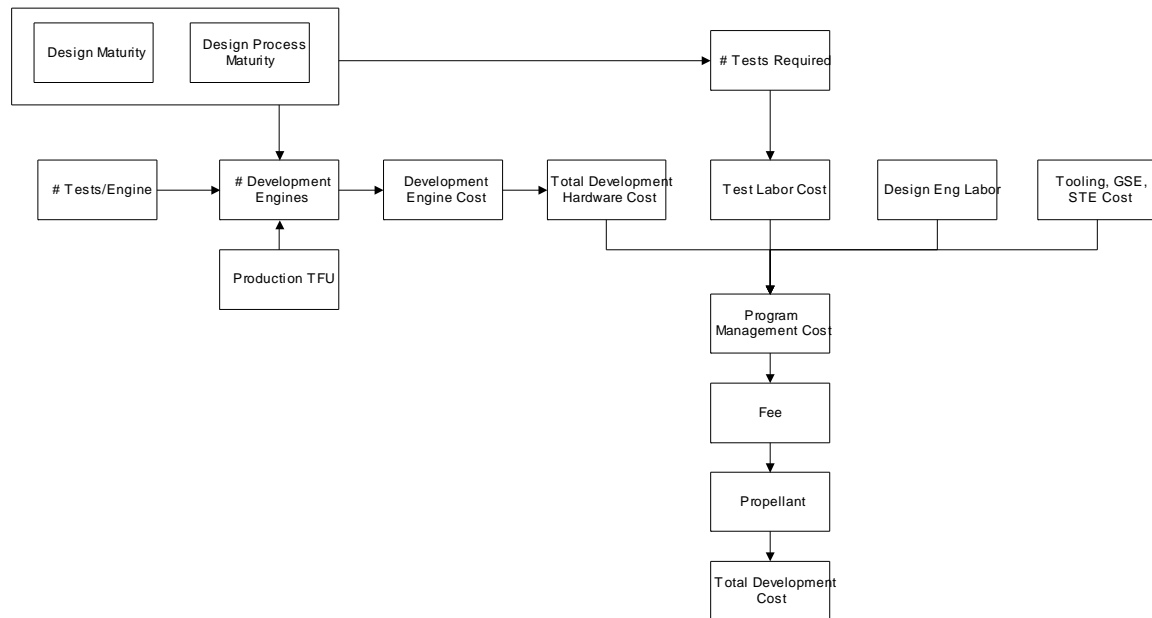
Figure 10. Development cost model structure.

These inputs are used in combinations to calculate the major cost impactors, such as the number of tests, and individually to produce the development cost. For the adjective inputs, RECM contains metric scales to convert them into numerical values.

The number of tests are influenced by three key parameters: the engine cycle complexity and severity of the internal engine environment, the engine design and manufacturing maturity (or state of the practice), and the engine certification approach. The latter is expressed as a process improvement factor. The multiplicative combination of the three parameters serves as an adjustment factor for the number of tests of

the reference case, i.e., for conditions other than the SSME.

The major driver for number-of-tests is the engine certification approach, followed by the engine design and manufacturing maturity. Engine cycle complexity has a moderate influence.

The certification approach represents the largest driver for test quantity. It can span a factor of 20 between the Apollo program approach and one for recertification of an out-of-production engine.

The engines for the Apollo program launch vehicle SATURN V required qualification at the engine component and at the engine system level, a formal demonstration of the 0.99 reliability goal at 50% confidence, resolution of all failure modes, and demonstration of all requirement changes by extensive testing. It was an approach dictated by a stringent program schedule with ample budget availability for a national program with high priority.

The SSME program used a new approach called "Design Verification Specification" which required engine design verification at the lowest level, i.e., either by engine hot fire testing, or by subsystem hot fire testing, or by component testing, or by analysis. No formal reliability demonstration was required; however, all failure disposition actions (UCRs) had to be demonstrated by successful testing. As a result, the number of tests to certification was considerably lower than for the F-1 and J-2.

The lowest number of tests were required for the resurrected ELV engines.

The minimum number of tests is about 20, for certification of a previously certified, "resurrected" engine that has been out of production for a long time. The maximum number of tests (about 2,000) is for a new engine with an Apollo program type certification approach.

Overall engine complexity, as expressed by the complexity of the thermodynamic cycle, is a moderate driver for test quantity. Test quantity can vary by a factor of two between the complex staged combustion (SSME type) and the simplest tap-off cycle engine. This factor is mainly influenced by the engine controllability and the number of parts in a single thrust chamber engine system. A more complex engine (e.g., with a topping cycle) usually has a more capable controller than a simple GG-type engine, which can reduce engine testing.

The engine design and manufacturing maturity factor reflects a judgment of the "newness" of an engine, i.e., its state-of-the-art in terms of design concept and/or manufacturing materials and processes use. The scale of the factor and the adjective descriptions are the same as those used in the PRICE-H parametric cost model.

The number of tests to certification can change by a factor of about 10, depending on whether the engine represents a simple modification of an existing design, or is new with advanced state-of-the-art in design and/or manufacturing processes or materials.

The number of actually needed equivalent new engines used in past PWR engine development programs varied between 1 and 53. Rebuilt engines and components for component testing are included in the engine count as a percentage of new engines.

The number of required development engines is dependent on the number of tests to certification (test quantity), and the average number of tests an engine can perform before it is retired because of life limitations or major failures. Judging from the historical data, it appears that "expensive" engines, i.e., engines with a high degree of complexity and low maturity can (on the average) be used 37 times, while "less expensive," low complexity, high maturity engines can be used 27 times before retirement.

The test process improvement input parameter is a measure of the efficiency of test labor due to improved tests, procedures, labor efficiency, etc. The design process improvement input parameter is a measure of advances in engineering tools and proficiency of the tool use.

The tooling improvement factor measures the cost effectiveness of tooling. It can be easily associated with the evolution of tooling sophistication by era. It reflects the impact of modular tooling, simplification, and reduced parts count on the cost of tooling.

The tooling availability factor measures the impact of the degree to which existing tooling is used, or conversely, the measure of tooling that must be designed or will be redesigned.

RECM Cost Model Summary

RECM is a top level parametric cost model generated for pump-fed liquid bipropellant booster and upper stage rocket engines in the 20 Klbs to 2,000 Klbs thrust class.

It covers production and full scale development costs and is based on thorough engineering analyses, not regression analysis, of data from historical PWR engines, potential engine derivatives and proposed new engine concepts. The models are not weight-based, but depend on thermodynamic cycle, propellant type, engine complexity, engine maturity and other design parameters. The model is simple, with a

documented transparent rationale, and the CERs were incorporated into a spreadsheet. The estimated uncertainty of both the production and development cost models is ±30% within the CER limits and within the thrust range of 20 Klbs to 2,000 Klbs.

Programmatic factors for production rate and quantity, and for development test frequency and hardware fabrication rate are included.

RECM makes use of adjective and objective parameters. For the adjective inputs, metric scales are given to convert them into numerical values. The adjective inputs require good engineering understanding of rocket engine design and manufacturing principles.

Several process improvement factors are incorporated to make the historical data based cost models applicable to new reusable advanced performance and/or to low cost engine concepts.

The validity and reasonableness of the cost models was successfully checked against STME and RS-68 data and against current manufacturing and programmatic analysis results of new engines.

Operations Cost Model Description

Operations cost models are particularly challenging because they attempt to estimate what it will cost to operate a system many years into the future, perhaps even a decade farther out than near term development. Again, there is the cost analyst's dilemma of getting information about the planned product early enough to affect the direction of the product's development, before design decisions are firmed up. Any inputs or assumptions that go into a cost estimate for operations so far out in time are inputs and assumptions that will likely change dramatically over that time. Therefore, the recurring operations cost estimate could have been done rigorously, with expert involvement, yet still be entirely incorrect and irrelevant, all because it is an estimate for something (with some organization) that never got built. The estimate would have been for the thing planned, not for the thing as it turned out.

To help address these issues, model development work at NASA Kennedy Space Center (KSC) has evolved ground operations models over the last decade to emphasize and communicate cost drivers, to emphasize the "why" as much as the analysis results, and to surface issues strategically, early in program/project definition. The Launch & Landing Effects Ground Operations (LLEGO) model[15] is one of the more recent developments in ground operations cost modeling. KSC analysts used LLEGO to support the recent Constellation program Standing Review Board (SRB) independent assessment process.

In LLEGO, cost model drivers are grouped into four basic categories. They can be dialed one way or another to affect the outcome, basically producing a cost for a desired capability. The idea of "all other things being equal" is used, as the categories have been kept rather segregated in the math of the cost model. For example, a decision to make a product more complex (for operations) will always increase costs (for the same capability, as in number of launches per year). However, another input (another decision) can make up for this, lowering the cost; for example, by setting up newer, more efficient, organizational support processes. The four categories of cost drivers do not mix and match arbitrarily in the real world, especially at the extremes, but an experienced cost analyst can identify these invalid points.

The four LLEGO cost model driver groups are:
1. Complexity
2. Reliability
3. Maintainability
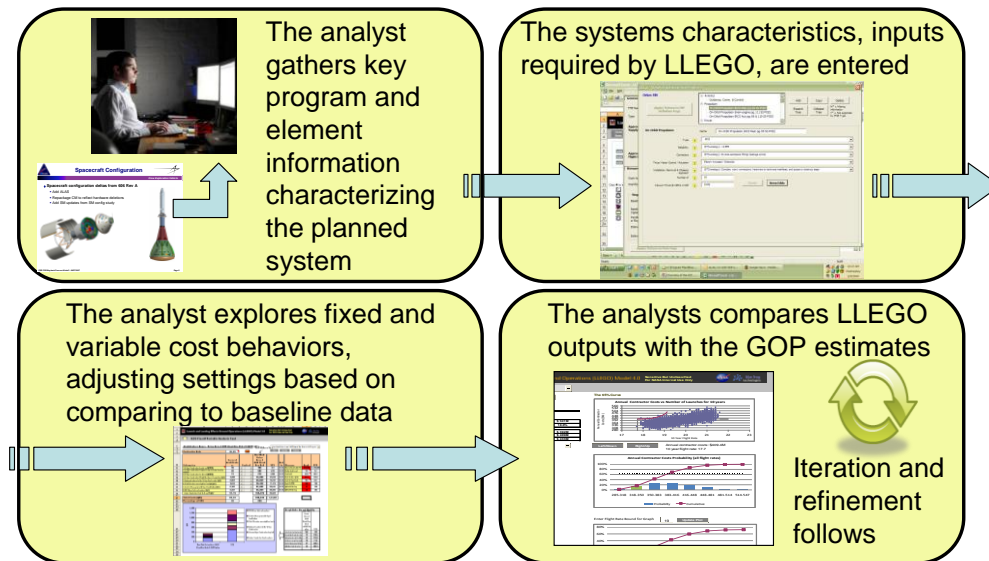4. Processes and Practices

For complexity, a design can start (or end up) with more or less distinct, interacting things (like engines, thrusters, sub-systems, flight or ground elements). For reliability, each of these may or may not fail at some target rate after delivery to the launch site, while being prepared for use. For maintainability, the repair of these can require more or less work, involving more or fewer hazards. For processes and practices, all this work can be performed and supported within organizational/technological processes and practices that flow information and materials more or less efficiently. A user might even decide to just fly less in order to reduce costs. Figure 11 shows the LLEGO model process.

Such a basic structure for thinking about all that is involved in determining the cost of planned operations is necessary in all aerospace (and other industry) products. LLEGO simply makes this structure more explicit, helping the analysts insert themselves into the design and definition process early, even seeking to generate a connection to early requirements. To use LLEGO estimates as actual values, the inputs into LLEGO must be part of the documented program/project requirements, or documentation, apart from any cost analysis documents. Otherwise LLEGO inputs are kept at "default", generating the most conservative estimates cognizant of practical uncertainties over time (a separate "LLEGO Joint Confidence

Level" feature is available). Alternately, should a program choose to lower an operations estimate, it is important that official program documentation be adjusted.

The process of analysis and interacting with the proposed program/projects is as important, if not more so, than the numbers generated. Sensitivity studies can assist in prioritizing where programs/projects can adjust.

- **Automating the process of calculating for applicable data, holistically adding up the effects to ground operations.**

The analyst gathers key program and element information characterizing the planned system

The systems characteristics, inputs required by LLEGO, are entered

The analyst explores fixed and variable cost behaviors, adjusting settings based on comparing to baseline data

The analysts compares LLEGO outputs with the GOP estimates

Iteration and refinement follows

Figure 11. The KSC LLEGO model process

Summary/Conclusions

During architecture studies and conceptual design studies, details of any new items to be traded are rarely known. Part counts, features of individual parts, the manufacturing processes to be used, and even the weight are not easily obtainable. WBS details are not available without large expenditures of effort. What is available are the major choices of parameters and the choices of how to produce and how to procure. Consequently, development and production cost models that do not need weight nor details about the hardware are especially useful for studies at these levels. An ideal model would include factors that allow examination not only of the change in cost due to design choices, but also the change in cost due to changes in approaches to manufacturing, testing, and oversight.

RECM and LLEGO are examples of such models. RECM has been incorporated by NASA into NAFCOM. It has also been successfully used by PWR for many contractual and internal efforts. LLEGO has been used by KSC.

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